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Effects of different water and fertilizer treatments on the matrix properties and plant growth of tailings waste

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Vegetation ecological restoration technology is widely regarded as an environmentally sustainable and green technology for the remediation of mineral waste. The appropriate ratio of amendments can improve the substrate environment for plant growth and increase the efficiency of ecological restoration. Herbs and shrubs are preferred for vegetation restoration in abandoned mines because of their rapid establishment and easy management. This study probed into their improvement effects on abandoned mine tailings from aspects such as plant growth and nutrient content. Based on this, the trail explored the impacts of different ratios of quarry waste matrix on different plant growth and the physical and chemical properties of the quarry matrix. The original soil, without fertilizer and with 45% water treatment, was taken as the control (CK), while the experimental group comprised of composite soil with different ratios of original soil and slag, combined with various water and nitrogen fertilizer treatments. *Pennisetum alopecuroides (L.) Spreng*, *Campsis grandiflora (Thunb.) Schum*, *Setaria glauca (L.) Beauv*, *Periploca sepium Bunge*, and mugwort (*Artemisia argyi Levl. Et Vant.*) were planted, respectively, in the control and experimental groups. After a 30-day period of nitrogen fertilizer and water treatment, an analysis was conducted to evaluate the physicochemical properties and growth status of the tailing matrix for different treatments. The results demonstrated that the M7 treatment significantly promoted the growth of mugwort, whereas the M2 treatment stimulated the growth of *Campsis grandiflora (Thunb.) Schum*. Additionally, the M3 treatment proved to be advantageous for enhancing the growth of *Setaria glauca (L.) Beauv*, *Pennisetum alopecuroides (L.) Spreng*, and *Periploca sepium Bunge*. The soil matrix pH of *Pennisetum alopecuroides (L.) Spreng*, *Campsis grandiflora (Thunb.) Schum*, *Setaria glauca (L.) Beauv*, *Periploca sepium Bunge*, and mugwort is all above 7.5, while macronutrient elements including TK, AK, TN, AN, TP, and AP exhibit varying degrees of enhancement. PCA analysis disclosed that there were significant disparities in substrate properties and plant growth properties among treatments for *Pennisetum alopecuroides (L.) Spreng*, *Campsis grandiflora (Thunb.) Schum*, *Setaria glauca (L.) Beauv*, *Periploca sepium Bunge*, and mugwort ($P < 0.05$). The correlation network and structural equation analysis revealed a significant positive correlation between the water and fertilizer matrix and soil AN and TN ($P < 0.05$). Additionally, TK exhibited a positive correlation with the growth status of all five plant species. Moreover, the water and fertilizer substrate displayed a positive association with the growth status of *Pennisetum alopecuroides (L.) Spreng*, *Setaria glauca (L.) Beauv*, *Periploca sepium Bunge*, as well as mugwort; however, it showed a negative correlation with the growth status of *Campsis grandiflora (Thunb.) Schum*.

The extensive extraction of mineral resources has led to a significant rise in tailings waste[1], which is characterized by its loose structure, limited water retention capacity, nutrient deficiencies and poses substantial environmental threats[2]. The environmental impact resulting from these activities persists over time and spans a wide geographical area with high intensity at the regional level[3]. Therefore, it is crucial to identify a more efficient approach for remediating tailings and managing waste effectively. Physical remediation techniques, along with chemical processes, are commonly employed methods; however, they

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are associated with disadvantages such as excessive costs and adverse effects on soil properties that may cause secondary pollution, thereby limiting their practicality. In contrast, vegetation ecological restoration technology has gained considerable prominence due to its remarkable efficacy[4].The key components of vegetation ecological restoration are plants and substrate, with a primary focus on local native species known for their robust adaptability. Equally vital is the substrate, which significantly influences vegetation ecological restoration through its composition of planting soil, fertilizers, and various additives. Different proportions impact both the hydrological properties of the substrate and its suitability for plant growth[5]. Therefore, it is crucial to augement the substrate with organic matter and essential nutrients to optimeze plant growth. Mining and transportation activities discrupt the inherent structure of the planting soil, leading to increased porosity, enhanced permeability, reduced shear strength, loose texture, and an unstable physical constitution. Consequently, when such modified soil is directly applied to compacted layers such as storage and transportation platforms without protective measures, it becomes highly susceptible to severe soil erosion, landslides, and other related geological disasters under the influence of wind and water[6,7].

Since the onset of the 21st century, infrastructure development in China has witnessed remarkable growth. This exponential growth in construction demands has consequently led to widespread unregulated mining activities, resulting in numerous exposed mines and residual tailings. In order to foster sustainable development and safeguard the ecological environment, government measures have been implemented to close down unauthorized mining operations extensively. However, addressing the persisting issue of tailings residues through ecological restoration remains an urgent imperative. In the process of mining and quarrying, waste can constitute up to 70% of the total volume of the quarry. The accumulation of such waste not only occupies extensive land areas but also cause landscape degradation and poses safety hazards. Proper disposal of quarry waste is crucial for ecological restoration in these regions[8,9]. Quarry waste can be effectively utilized as a raw material in concrete and ceramic tile production, as well as a construction material for highways[10]. However, most research predominantly focused on fine particles smaller than 4–5 mm, with limited studies addressing coarse-grained slag[11,12]. This coarse slag presents a loose structure with particles typically in point contact. It is characterized by its high bulk capacity, high shear strength, low subsidence deformation, and high permeability. These properties complement the low shear strength and high compressibility observed in sieved soil[13]. Gravel is commonly employed as a surface cover material that provides protection against direct impact from wind flow, wind-sand erosion, and rainfall. Numerous studies suggest that gravel coverage effectively reduces slope runoff and soil erosion[14,15]. Within soils containing gravel content correspond to delayed onset of flow production on slopes and alterations in both the quantity and rate of soil infiltration[15].

The incorporation of coarse gravel derived from quarrying operations with sieved soil can create a suitable substrate promoting plant growth. This approach not only enhances the physical properties of the sieved soil but also reduces the volume of quarry spoil in the vegetative restoration effects at quarry sites. In this study, different ratios were examined to establish an optimal planting substrate consisting of sieved soil and gravel, speficially designed for promoting plant growth during the rehabilitation process of quarry sites. Laboratory potting experiments were conducted to evaluate both the physical and chemical characteristics of the substrate and monitored plant growth. Aiming to address the challenge of effectively blending sieved soil with coarse-grained quarry waste in vegetation restoration.

Result

Effects of different water and fertilizer treatments on plant growth parameters

As shown in Fig. 1, significant variations were observed among the treatments with regards to plant height, stem and leaf dry weight, stem and leaf fresh weight, as well as root dry weight of Pennisetum ($P<0.001$). Notably, the M2, M3, and M7 treatments demonstrated significantly higher plant height and stem and leaf dry weight in compared to other treatments ($P<0.001$). Furthermore, the M2, M3, and M5 treatments showed significantly greater stem and leaf fresh weight along with root dry weight than other treatments ($P<0.001$). Regarding Campsis grandiflora (Thunb.) Schum (Cg), significant variations were observed among the treatments in terms of plant height, dry weight of stems and leaves, fresh weight of stems and leaves, and dry root weight ($P<0.05$). The M2 treatment revealed significantly higher values for plant height, dry weight of stems and leaves, fresh weight of stems and leaves, and dry root weight compared to the other treatments *(*$P<0.05$*)*. In relation to *Setaria glauca (L.) Beauv (Sg)*, there were significant differences between the treatments in the dry weight of stem and leaf, the fresh weight of stem and leaf, and root dry weight ($P<0.05$). The plant height of treatments CK, M3, and M7 exceeded that of the remaining treatments. Futhermore, the fresh weight of stems and leaves of the M3 and M7 treatments was significantly higher than that of the others ($P<0.05$). Moreover, among all treatments including M2, M3, M5, M7, and M9 treatments, only the plant height and leaf fresh weight reached their peak level in the treatment with an application rate of M3. For *Periploca sepium Bunge* (Ps), there were significant variations were observed among different treatments regarding stem and leaf dry weight, stem and leaf fresh weight as well as root dry weight ($P<0.05$), while no significant difference was observed in plant height among various treatments. The M3 treatment manifested significant increase in stem and leaf fresh weight, as well as root dry weight compared to the other treatments ($P<0.05$). Moreover, the plant height of the M3 treatment was higher than that of the others. Notably, mugwort (Ag) showed variations among treatments in terms of stem and leaf dry weight, as well as dry root weight ($P<0.05$), while no significant difference was found in plant height between the treatments. The plant height of

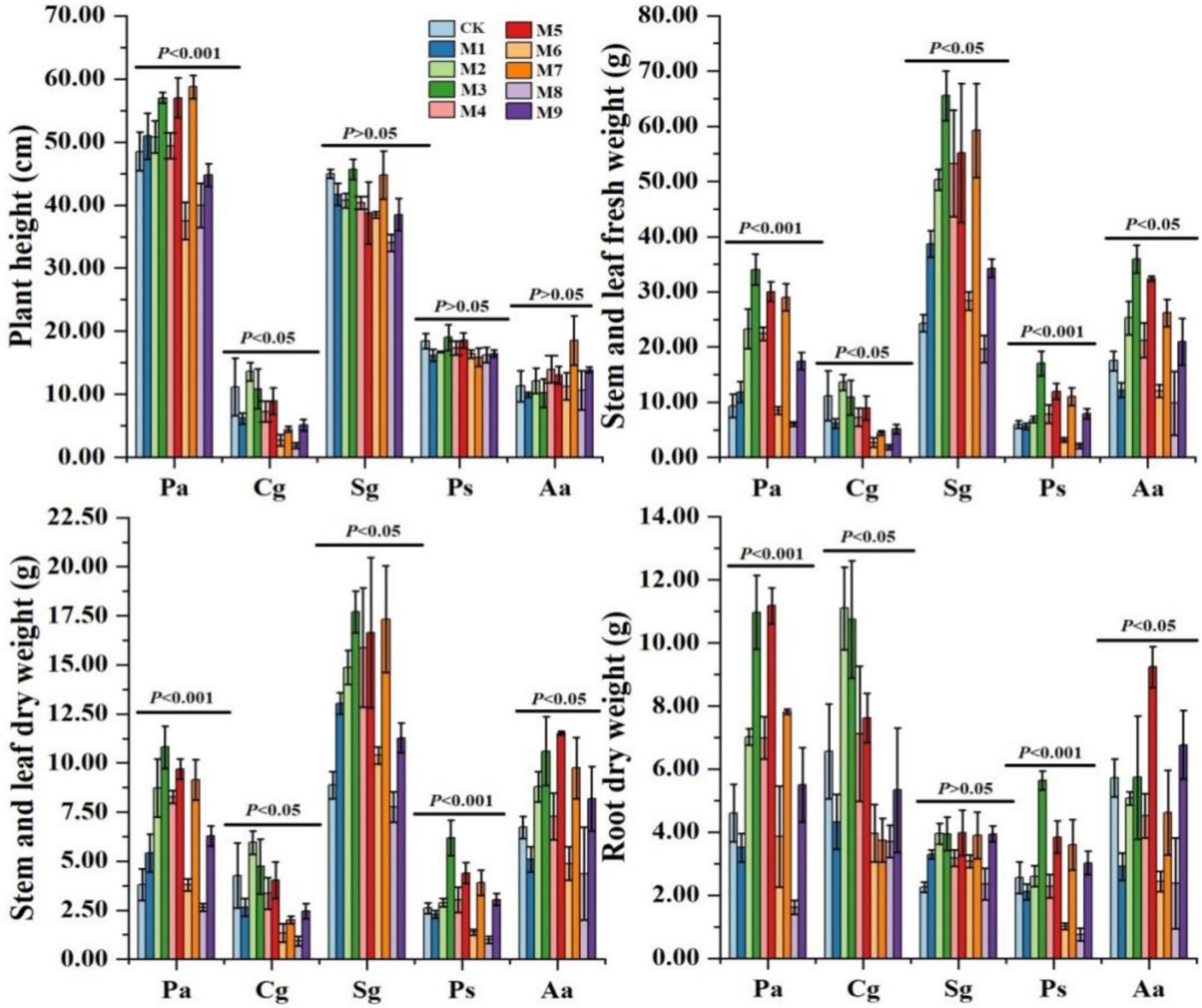

Fig. 1. Effects of different water and fertilizer treatments on plant growth parameters. *Pa Pennisetum alopecuroides (L.) Spreng*; *Cg Campsis grandiflora (Thunb.) Schum*; *Sg Setaria glauca (L.) Beauv*; *Ps Periploca sepium Bunge*; *Aa Artemisia argyi Levl. Et Vant*.

the M7 treatment exhibited significant higher values compared to the remaning treatments ($P<0.05$). Additionally, the fresh weight of stems and leaves in M3 treatment demonstrated significantly higher values compared to the remaning treatments ($P<0.05$), while both stem and leaf dry weight, as well as root dry weight, were significantly higher than those of the others ($P<0.05$).

Effects of different water and fertilizer treatments on the physical and chemical properties of the mixed matrix

As illustrated in Fig. 2, the pH of Sg was significantly higher than that of the other plants ($P<0.05$). With regard to TN content, Aa showed significantly higher levels than the other plants in M2 and M8 ($P<0.05$). Additionally, Ps demonstrated significantly higher TN levels in M3, M4, and M7 ($P<0.05$). The TN content in the soil of Cg in the M6 treatment was significantly higher than that of the other plants, while the M9 treatment showed significantly lower TN levels ($P<0.05$). Regarding TK, the soil of Sg in the M1, M2, M3, M4, and M5 treatments had significantly higher TK levels compared with the other plants. In contrast, the soil of Aa in all treatments showed significantly lower TK content compared with the other plants ($P<0.05$). The TK content in the soil of Cg in M6, M7, and M9 treatments was significantly higher, while the TK content in the soil of Pa in M8 treatment was significantly higher ($P<0.05$). The analysis of soil TP revealed that the content in Pa and Cg in M1, M2, M3, M4, and M5 treatments was significantly higher than that of the other plants ($P<0.05$). As shown in Fig. 3, the available nitrogen content in Cg for M1, M4, M6, M7, and M8 treatments was significantly higher than that of the other plants, while the available nitrogen content in Sg for M1, M2, M4, M6, M7, M8, and M9 treatments was significantly lower

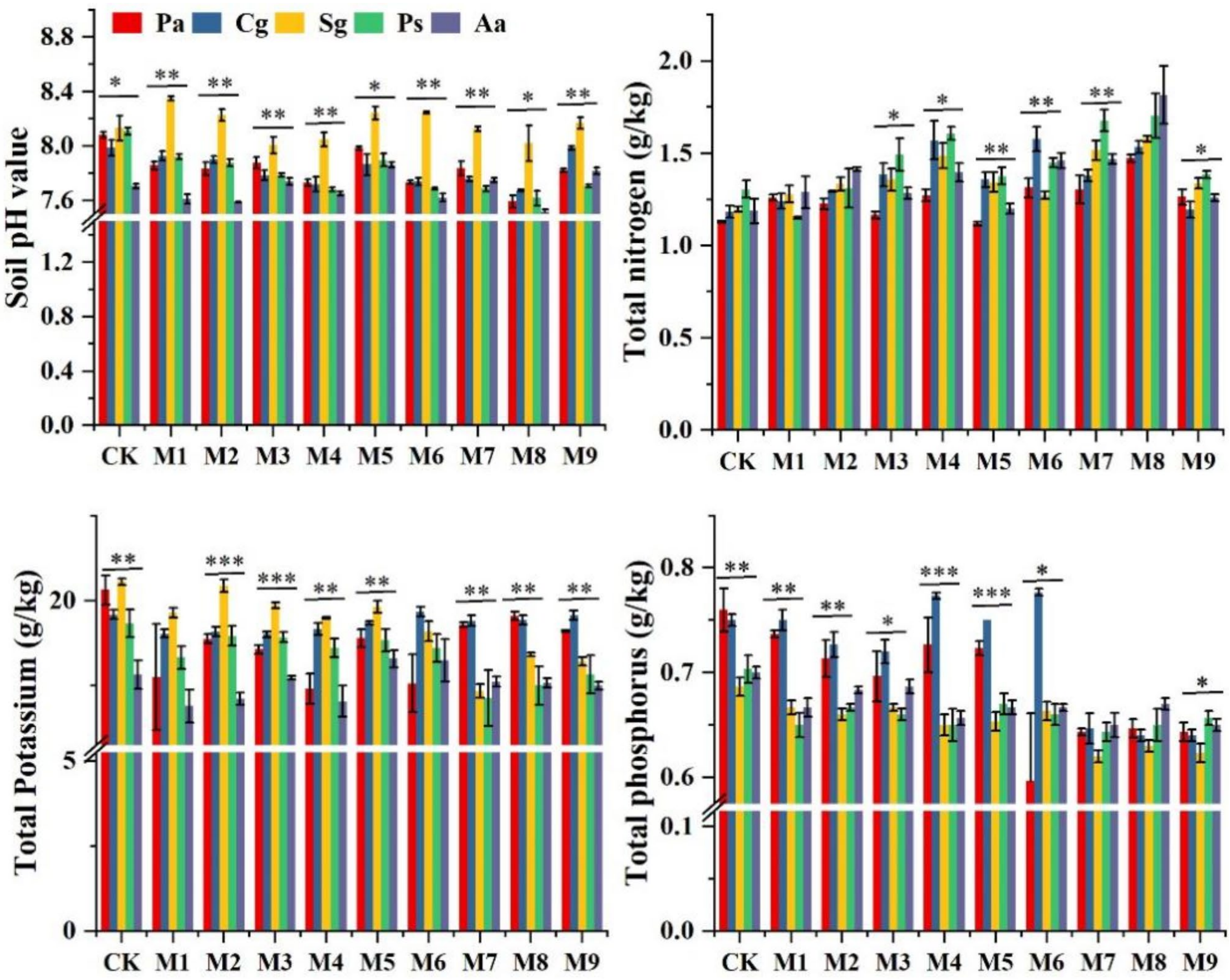

Fig. 2. Effects of different water and fertilizer treatments on the total nutrients of the mixed matrix. *Pa Pennisetum alopecuroides (L.) Spreng*; *Cg Campsis grandiflora (Thunb.) Schum*; *Sg Setaria glauca (L.) Beauv*; *Ps Periploca sepium Bunge*; *Aa Artemisia argyi Levl. Et Vant*. The asterisk indicated a significant difference between different plants (*$p < 0.05$, **$0.01 < p < 0.05$, ***$p < 0.01$).

than that of the other plants ($P < 0.05$). Additionally, the available nitrogen content in Ps for M2, M3, and M9 treatments was significantly higher than that of the other plants ($P < 0.05$). The analysis of soil AK disclosed that the AK content in Cg for M2, M4, M5, M6, M7, M8, and M9 treatments was significantly higher than that of the other plants ($P < 0.05$). Additionally, the analysis of soil AP indicated that Cg had significantly higher AP content in all treatments compared to the other plants ($P < 0.05$).

PCA analysis of mixed substrate properties and plant growth under different water and fertilizer treatments

Principal coordinate analysis (PCA) based on the Bray-Curtis algorithm was applied to analyze the variations in the mixed matrix properties and plant growth conditions of the tailings waste, and to determine the influences of different water and fertilizer treatments on the matrix properties and plant growth of the tailings waste (Fig. 4). The total variance accounted for Pa, Cg, Sg, Ps, and Aa exceeded 60%, with an $R > 0$. This hights distinct differences in the tailings waste matrix and plant growth properties under different water and fertilizer treatments. The ANOSIM test indicated that water and fertilizer treatment significantly affected the substrate properties and plant growth properties of Pa, Cg, Sg, Ps, and Aa ($P < 0.05$).

Correlation ecological network analysis of physical and chemical properties of mixed matrix and plant properties

An ecological network analysis demonstrated the correlation between the physical and chemical properties of tailings waste and plant properties, as presented in Fig. 5. For Pa and Cg, pH and total phosphorus (TP)

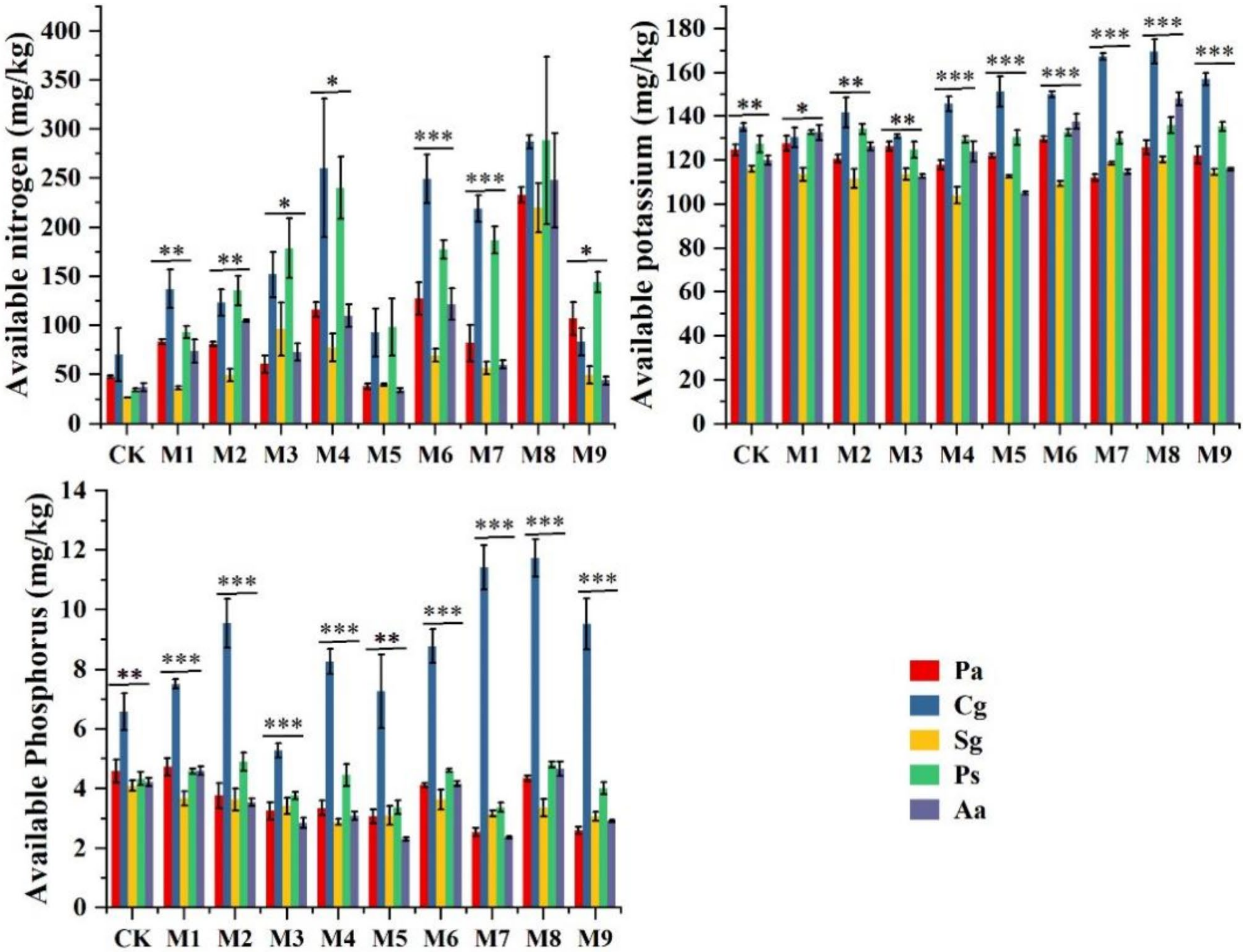

Fig. 3. Effects of different water and fertilizer treatments on the available nutrients of the mixed matrix. *Pa Pennisetum alopecuroides (L.) Spreng*; *Cg Campsis grandiflora (Thunb.) Schum*; *Sg Setaria glauca (L.) Beauv*; *Ps Periploca sepium Bunge*; *Aa Artemisia argyi Levl. Et Vant*. The asterisk indicated a significant difference between different plants (*$p < 0.05$, **$0.01 < p < 0.05$, ***$p < 0.01$).

were positively correlated with root dry weight, plant height, fresh weight of stem and leaf, and dry weight of stem and leaf. A significant positive correlation was also noted between root dry weight, plant height, fresh weight of stem and leaf, and dry weight of stem and leaf. For Sg, pH showed a positive correlation with root dry weight, plant height, fresh weight of stem and leaf, and dry weight of stem and leaf. TP and AP were positively correlated with plant height, while TK demonstrated positive correlations with plant height, fresh weight of stem and leaf, and the dry weight of stem and leaf. TN was positively correlated with fresh weight of stem and leaf and dry weight of stem and leaf. Additionally, a significant positive correlation was observed between root dry weight, plant height, the fresh weight of stem and leaf, and the dry weight of stem and leaf. For Ps, TK, TP, and pH all displayed positive correlations with root dry weight, plant height, the fresh weight of stem and leaf, and the dry weight of stem and leaf. Conversely, TN was positively related with plant height and stem and leaf weights. Notably, a significant positive correlation was found between root dry weight, plant height, the fresh weight of stem and leaf, the dry weight of and stem and leaf. In Aa, pH presented a positive correlation with root dry weight, plant height, the fresh weight of stem and leaf, and dry weight of stem and leaf, while both TP and TK were positively correlated with root dry weight and stem and leaf weights.

Structural equation model analysis of physical and chemical properties of mixed matrix and plant properties

A Structural Equation Model (SEM) was applied to analyze the impact of diverse water and fertilizer treatments on the physicochemical and plant traits of tailings waste (Fig. 6). The combined influences of water-fertilized substrate and soil physicochemical attributes accounted for the observed plant growth patterns. In the instance of Pa, these combined factors accounted for 83% of the variation in plant growth. The water-fertilizer substrate had a significant and positive influence on plant growth. Meanwhile, pH and

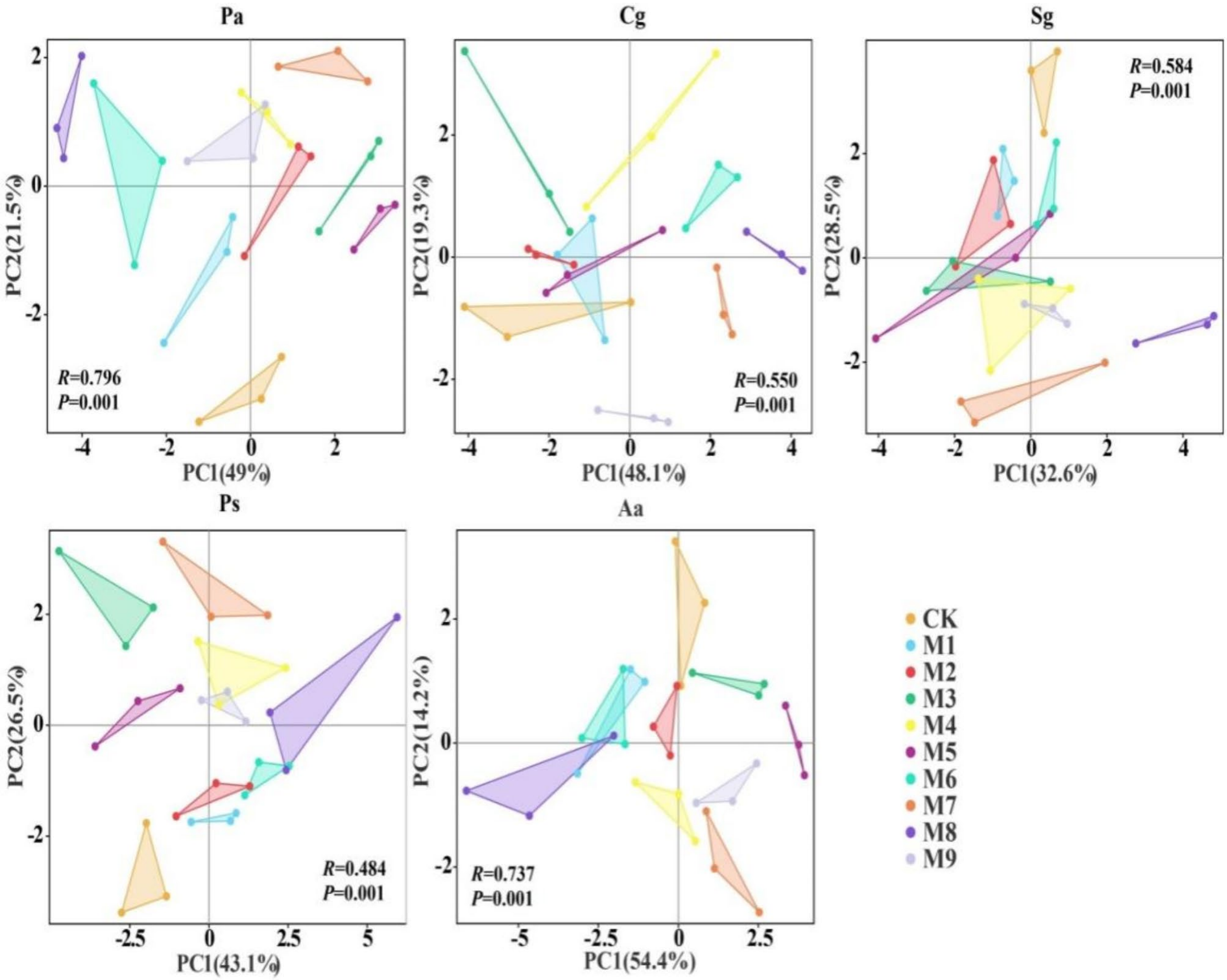

Fig. 4. PCA analysis of mixed substrate properties and plant growth under different water and fertilizer treatments. *Pa Pennisetum alopecuroides (L.) Spreng*; *Cg Campsis grandiflora (Thunb.) Schum*; *Sg Setaria glauca (L.) Beauv*; *Ps Periploca sepium Bunge*; *Aa Artemisia argyi Levl. Et Vant*.

TK had a direct, albeit not statistically significant, positive influence on plant growth. Conversely, AP and AN had a significant negative impact on plant growth. Water-fertilized substrates manifested significant direct positive effects on both TN and AN while showing significant direct negative effects on pH and TK. For Cg, the combined effect of the water-fertilizer substrate and soil physicochemical characteristics accounted for 43% of the variation in plant growth. AN showed a significant and direct positive influence on plant growth, whereas TK exerted a direct positive influence, though it was not statistically significant. Additionally, the water-fertilizer substrate had a significant and direct positive influence on TN and AN but a negative influence on pH. For Sg, the combined factors of water, fertilizer substrate, and soil physicochemical properties accounted for 52% of the variance in plant growth. The water-fertilizer substrate had a significant and positive effect on plant growth. While TN, AK, and TK had positive effects on plant growth, these effects were not statistically significant. Conversely, AP and AN had significant and negative effects on plant growth. Moreover, water-fertilized substrates significantly raised the levels of TN and AN. For Ps, a combination of water, fertilizer substrate, and soil physicochemical properties accounted for 65% of the variance in plant growth. The water-fertilizer substrate, TN, pH, and TK had positive effects on plant growth, although these were not statistically significant. In contrast, AK and TP had significant and negative effects on plant growth. Furthermore, the water-fertilizer substrate significantly elevated the AN level while adversely affecting pH. For Aa, the combined influence of water, fertilizer substrate, and soil physicochemical properties accounted for 70% of the variation in plant growth. Although the water-fertilizer substrate, TP, and TK had positive effects on plant growth, these were not statistically significant. Notably, the water-fertilizer substrate significantly elevated the levels of AN, TN, and AK, while concurrently lowering pH values.

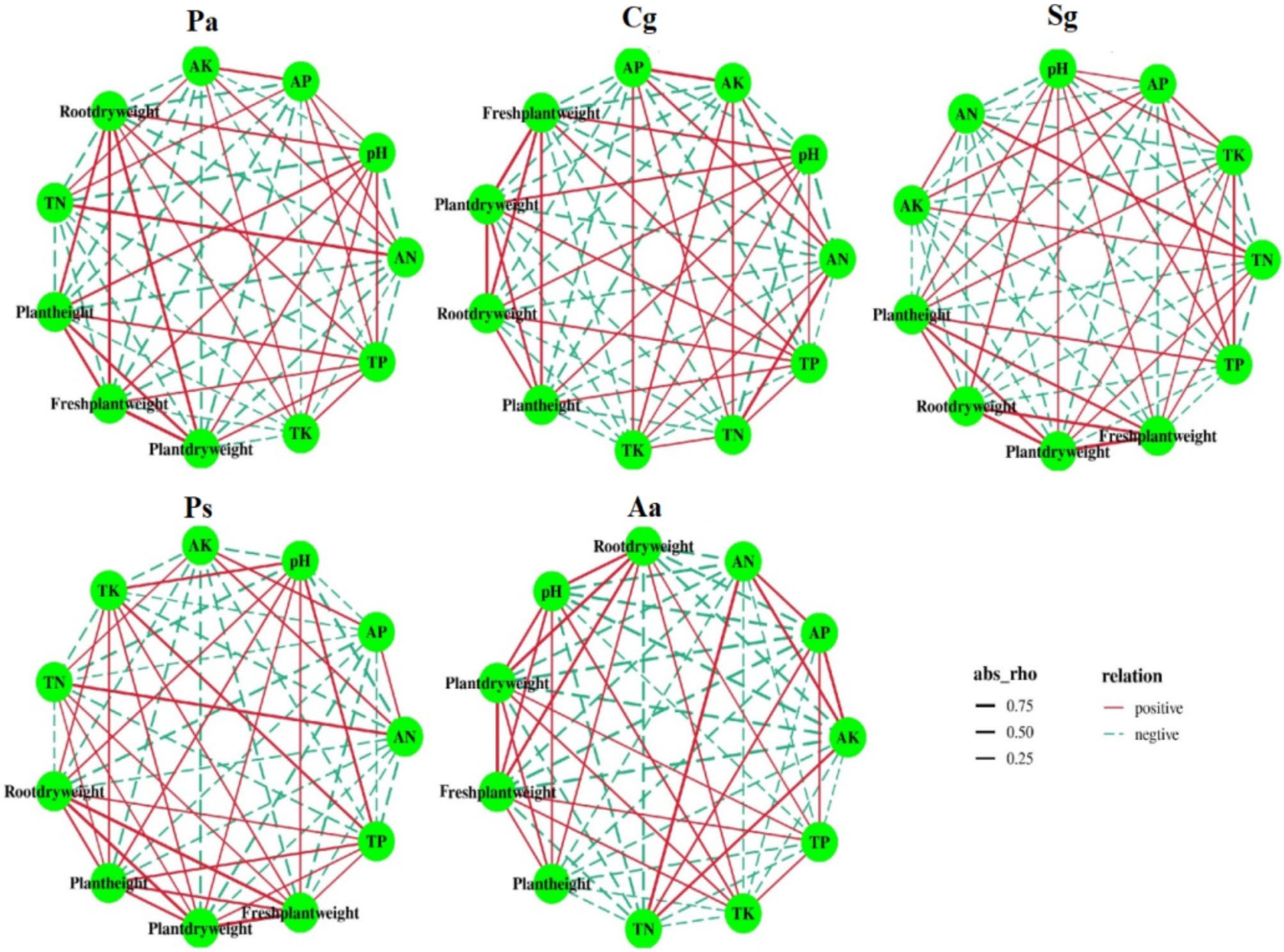

Fig. 5. Ecological network related to physical and chemical properties of tailings waste and plant properties. *Pa Pennisetum alopecuroides (L.) Spreng*; *Cg Campsis grandiflora (Thunb.) Schum*; *Sg Setaria glauca (L.) Beauv*; *Ps Periploca sepium Bunge*; *Aa Artemisia argyi Levl. Et Vant*. *TN* total nitrogen; *TP* total phosphorus; *TK* total potassium; *AN* alkaline hydrolysis of nitrogen; *AP* available phosphorus; *AK* available potassium.

Discussion

Soil nutrients constitute the basis for plant growth and development, and vegetation plays a prominent and decisive role in soil nutrient availability and biological processes[16]. Plants cultivated on tailings usually present stunted growth and withered stems and leaves. This is predominantly attributed to the limited nutrient content of the tailings substrate, the poor water retention capacity, and the absence of crucial elements such as organic matter, nitrogen, and phosphorus, which are indispensable for plant growth[17]. In comparison with other slag substrate ratios, the plant height, as well as the dry weight of stem and leaf, in treatments M2, M3, and M7 were significantly higher than those in the other treatments. Additionally, the fresh weight of stem and leaf and dry weight of root in treatments M2 and M3 were significantly greater than those in the other treatments. This improvement can be predominantly attributed to the organic matter content of the conditioner and the abundant nutrients present in the original soil, which jointly provide sufficient nutrients essential for plant growth. Furthermore, water supplementation enhances the water retention capacity of the substrate, thereby further enhancing soil fertility[18]. This correlation was further verified by the positive correlation of plant height, the dry weight of stem and leaf, the fresh weight stem and leaf, and root dry weight with the nutrient elements of the tailing substrate. The main mechanism of action could be that the nitrogen-phosphorus-potassium-source amendments enhance the metabolic activity of soil microorganisms, which facilitates the soil maturation process of the tailings substrate and promotes the settlement and growth of plants[19–21]. The observations are consistent with the findings from previous research. Specifically, Pardo et al. enhanced mine soil using pig manure and compost, noting a significant increase in the contents of water-soluble carbon, water-soluble nitrogen, available phosphorus, and available potassium in the treated soil—factors that collectively facilitated plant growth[22,23]. However, there was no plant growth in the N treatment at 18 months and 30 months after vegetation restoration. This might be related with the loose structure of the tailings. Merely employing available nitrogen fertilizers, such as urea, exposes the soil to a high leaching potential, leading to a nitrogen deficiency

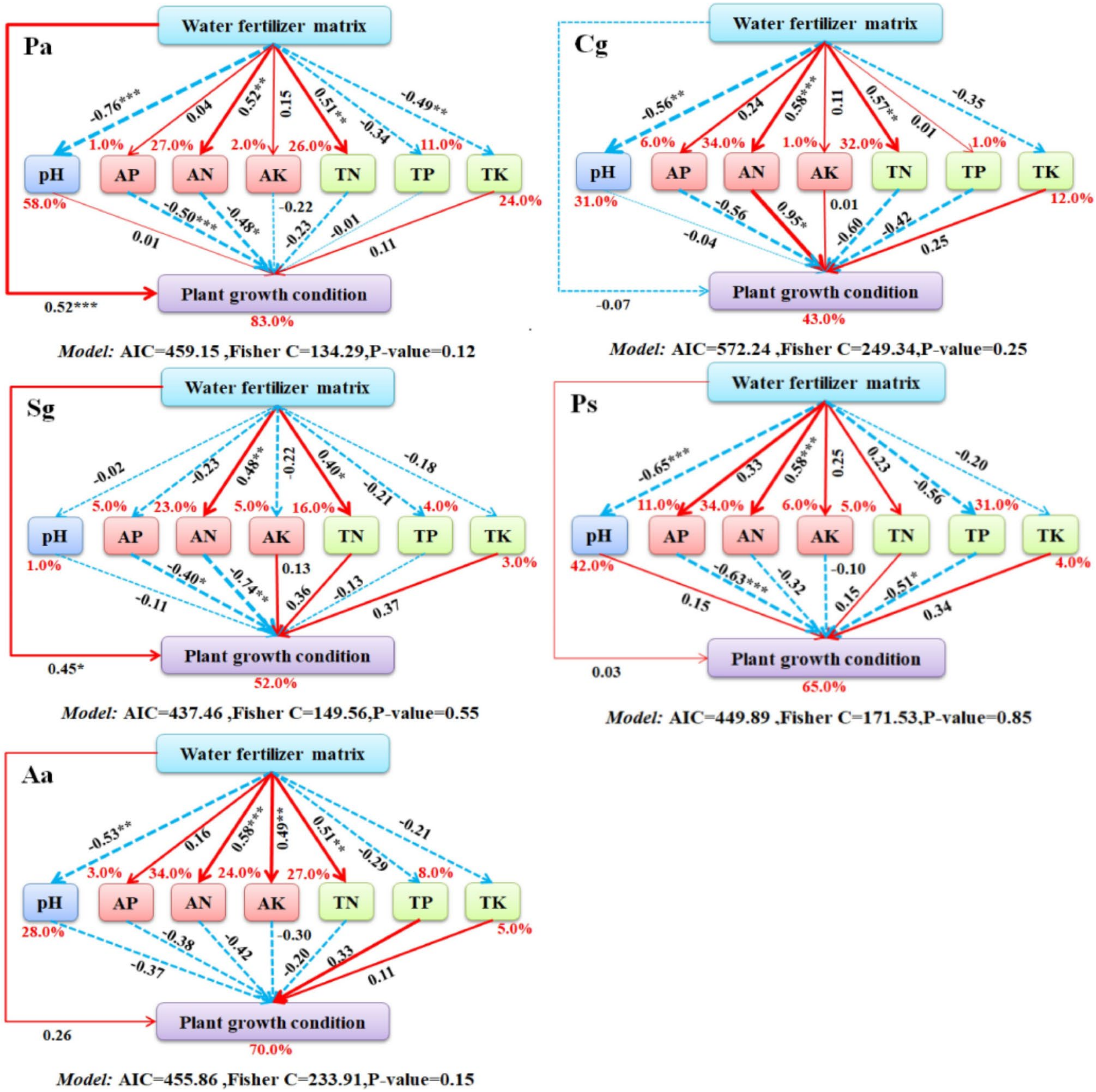

Fig. 6. Structural equation model of physical and chemical properties of mixed matrix and plant properties. *Pa Pennisetum alopecuroides (L.) Spreng*; *Cg Campsis grandiflora (Thunb.) Schum*; *Sg Setaria glauca (L.) Beauv*; *Ps Periploca sepium Bunge*; *Aa Artemisia argyi Levl. Et Vant*. *TN* total nitrogen; *TP* total phosphorus; *TK* total potassium; *AN* alkaline hydrolysis of nitrogen; *AP* available phosphorus; *AK* available potassium.

in subsequent growth stages and causing seedling mortality[24,25]. A larger chemical composition of the conditioner and water does not lead to enhanced plant growth. According to Li et al.[26], 5%, 10%, and 15% of attapulgite and biochar were respectively added to complex heavy metal contaminated soil, and the combined application of 10% attapulgite and 10% biochar has the most favorable growth-promoting effect on ryegrass.

Soil pH significantly influences soil activity, and modifications in microbial substances directly influence the metabolism, growth, and development of both plants and organisms. The pH level is closely related with critical physical and chemical properties of the soil[27]. In this study, the soil matrix pH for *Pennisetum alopecuroides (L.) Spreng*, *Campsis grandiflora (Thunb.) Schum*, *Setaria glauca (L.) Beauv*, *Periploca sepium Bunge*, and mugwort consistently exceeded 7.5, indicating alkalinity. Furthermore, the nutrient levels of these soils are within the optimal pH range. The increased alkalinity of tailings primarily result from the anions of alkaline substances absorbing the cations of the tailings[28]. The inherently low pH of the original soil can either neutralize the alkalinity of the tailings or, potentially, the selective enrichment of alkaline ions within the plant rhizosphere can lower soil alkalinity[29]. From another perspective, the application of compound amendments enhances the pH-improving effect of herbs and is beneficial for tailings remediation.

Soil nutrients are of crucial significance for plant growth and development[30]. Plants can either directly absorb mineral nutrients such as nitrogen, phosphorus, and potassium from the soil or assimilate them after transformation[31]. The composite improver elevated the levels of macronutrients in the tailings, including TK, AK, TN, and AP. This enrichment is probably attributed to the combined effects of the original soil, nitrogen fertilizers, and water, which enhanced the nutrient content, particularly N, P, and K[32]. In contrast to the CK group, the AK content in the planting areas treated with compound amendments showed an upward trend. The main source of this potassium is from the potassium-bearing minerals within the parent material of the soil[33]. Nevertheless, as the soil's pH decreases, its potassium fixation capacity reduces. Consequently, there is a rise in the AK content of the tailings, and the slow-releasing potassium in the tailings is transformed into readily available forms. Simultaneously, the soil undergoes an increase in H^+ concentration, non-specifically adsorbed potassium in colloids, water-soluble potassium, and exchangeable potassium, all exerting influences on plant responses[33]. Additionally, the contents of total phosphorus and available phosphorus in each plant planting area were lower than those in the CK treatment. This reduction might be attributed to the alteration in soil pH affecting phosphorus content. As water-soluble phosphorus is gradually released and assimilated by plants, the effective phosphorus content of the tailings declines[34]. Furthermore, in alkaline soils, phosphorus readily reacts with calcium, mainly forming low-solubility calcium phosphate salts, which restrict the availability of phosphorus and result in a decreased effective phosphorus content[35].

Conclusions

In conclusion, a mixture of raw soil and slag primarily serves as a substrate for plants. Distinct from previous studies, this research employs a combination of original soil, slag, nitrogen fertilizer, and water as amendments for tailings remediation. Tailings replace guest soil as the substrate for plant growth in the ecological restoration of mines. The results susggest that the application of compound amendments can significantly improve the physical and chemical properties of tailings and facilitate plant growth. The M5 treatment was conducive to the growth of *Pennisetum alopecuroides (L) Spreng* and mugwort, the M2 treatment was beneficial to the growth of *Campsis grandiflora (Thunb.) Schum*, and the M3 treatment was favorable to the growth of *Setaria glauca (L) Beauv* and *Periploca sepium Bunge*. Hence, applying an appropriate proportion of compound amendments to plants more effectively the comprehensive physical and chemical properties of tailings. Additionally, on the basis of this research, future studies could be concentrated on enhancing the vegetation ecological restoration technology effect and microbial activity of tailings through compound amendments.

Materials and methods

Experimental materials

The study applied highly stress-resistant native plants such as *Pennisetum alopecuroides (L.) Spreng*, *Campsis grandiflora (Thunb.) Schum*, *Setaria glauca (L.) Beauv*, *Periploca sepium Bunge*, and mugwort (*Artemisia argyi Levl. Et Vant.*), which mature seeds collected in 2020. The field topsoil selected as the planting medium is characterized by the following properties: a pH value of 7.78, an organic matter content of 18.20 g/kg, total nitrogen of 1.69 g/kg, total phosphorus of 0.68 g/kg, total potassium of 20.53 g/kg, alkali-hydrolyzable nitrogen of 58.20 mg/kg, available phosphorus of 3.08 mg/kg, and available potassium of 165.94 mg/kg.

Experimental design

The plant pot screening test conducted a three-factor pot control experiment, focusing on substrate, fertilizer, and water (Table 1). The three substrate treatments had diverse mixing ratios of raw soil to slag (with a particle size of ≤ 1 ~ 2 cm), namely 2:1, 1:1, and 1:2. Each pot was filled with a 2500 g mixture. For the three nitrogen fertilizer treatments, urea was adopted as the nitrogen source. The amount applied was converted to the equivalent quantity per unit area of flower pot soil, based on the field application rate and area, with the planting layer depth calculated as 20 cm. Specifically, the application rates were 1 g, 2 g, and 3 g per pot respectively, and the corresponding field application rates were 200 kg/km^2, 400 kg/km^2, and 600 kg/km^2 respectively. The three water treatments respectively corresponded to 30%, 45%, and 60% of the maximum field water holding capacity. By utilizing the orthogonal experimental design and including controls, the study incorporated a total of 10 treatments. Each treatment had three replicates, resulting in 30 pots per plant. The original soil, without fertilizer and with 45% water treatment, was utilized as the control (CK).

Experimental test indicators and methods

Seedling cultivation was conducted in the greenhouse. Once the seedlings had fully emerged, uniformly developed specimens were selected for transplantation. Subsequently, a controlled potted experiment was initiated to investigate the impacts of water and fertilizer stress. Nitrogen fertilizer was applied in stages, and water control commenced upon reaching the designated treatment level. Watering was carried out

Treatment naming	Treatment		
	A: matrix	B: water (%)	C: urea (g)
M1	Original soil: slag = 2:1	30	1
M2	Original soil: slag = 2:1	45	2
M3	Original soil: slag = 2:1	60	3
M4	Original soil: slag = 1:1	45	3
M5	Original soil: slag = 1:1	60	1
M6	Original soil: slag = 1:1	30	2
M7	Original soil: slag = 1:2	60	2
M8	Original soil: slag = 1:2	30	3
M9	Original soil: slag = 1:2	45	1
CK (control)	Original soil	45	0

Table 1. Orthogonal experimental design.

gently to maintain this level. The stress treatment was concluded after 30 days of simultaneous nitrogen and water regulation. After recording the plant height, the above-ground plant parts were harvested, and both soil samples and plant roots were collected. Plant samples were dried at 105℃ to determine the dry weights of stems, leaves, and roots. The pH of the soil was measured by using a pH meter with a soil-to-water ratio of 1:2.5 extract. Soil organic carbon (SOC) was calculated through the dichromate oxidation method[36]. Soil total nitrogen (TN) was determined by using the Kjeldahl method[37]. The molybdenum blue method was adopted to determine soil total phosphorus (TP)[38]. Flame photometry was utilized to measure soil total potassium (TK) and available potassium (AK)[39]. Alkaline hydrolysis nitrogen (AN) was measured by using the alkaline hydrolysis diffusion method. Soil available phosphorus (AP) was determined via the application of the Olsen method[40].

Statistical analyses

The significance of the differences between soil physical and chemical indicators and plant growth status indicators was analyzed through one-way analysis of variance (ANOVA) and multiple comparisons (LSD method, $P = 0.05$) within SPSS 26.0 software. Principal component analysis (PCA) was executed using the R software "stats" package. Through dimensionality reduction, the similarities and dissimilarities among plants were qualitatively analyzed to identify the potential principal components that affect plant composition differences. In order to further ascertain whether the differences between groups are statistically significant, the R software "vegan" package was utilized to conduct ANOSIM analysis to test the significance of the differences. The Pearson test mainly analyzes the correlation between plant growth conditions and physical and chemical factors through the correlation ecological network. The histogram is drafted using Original 2021, which mainly analyzes soil physical and chemical indicators and plant growth status indicators, and AI (Adobe Illustrator CS6) software is utilized for graphic modification.

Data availability

The datasets used and/or analyzed during the current study available from the corresponding author on reasonable request.

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Declarations

Competing interests

The authors declare no competing interests.

Research statement involving plants
Experimental research and field studies on plants (either cultivated or wild), including the collection of plant material, was carried out in accordance with relevant institutional, national, and international guidelines and legislation.

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